Environmental Management (2018) 61:469–480
DOI 10.1007/s00267-017-0941-1

Adaptive Management of Environmental Flows: Using Irrigation Infrastructure to Deliver Environmental Benefits During a Large Hypoxic Blackwater Event in the Southern Murray–Darling Basin, Australia

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Received: 10 August 2016 / Accepted: 7 September 2017 / Published online: 19 September 2017
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Abstract Widespread flooding in south-eastern Australia in 2010 resulted in a hypoxic (low dissolved oxygen, DO) blackwater (high dissolved carbon) event affecting 1800 kilometres of the Murray–Darling Basin. There was concern that prolonged low DO would result in death of aquatic biota. Australian federal and state governments and local stakeholders collaborated to create refuge areas by releasing water with higher DO from irrigation canals via regulating structures (known as 'irrigation canal escapes') into rivers in the Edward–Wakool system. To determine if these environmental flows resulted in good environmental outcomes in rivers affected by hypoxic blackwater, we evaluated (1) water chemistry data collected before, during and after the intervention, from river reaches upstream and downstream of the three irrigation canal escapes used to deliver the environmental flows, (2) fish assemblage surveys undertaken before and after the blackwater event, and (3) reports of fish kills from fisheries officers and local citizens. The environmental flows had positive outcomes; mean DO increased by 1–2 $\mathrm{mg\,L^{-1}}$ for at least 40 km downstream of two escapes, and there were fewer days when DO was below the sub-lethal threshold of 4 $\mathrm{mg\,L^{-1}}$ and the lethal threshold of 2 $\mathrm{mg\,L^{-1}}$ at which fish are known to become stressed or die, respectively. There were no fish deaths in reaches receiving environmental flows, whereas fish deaths were reported elsewhere throughout the system. This study demonstrates that adaptive management of environmental flows can occur through collaboration and the timely provision of monitoring results and local knowledge.

Keywords Environmental flows · Blackwater · Dissolved oxygen · Fish kills · Refugia · Adaptive management

Introduction

During flood events, inundation of riverbanks or the floodplain and the subsequent decomposition of organic material can produce 'blackwater' containing high dissolved organic carbon (DOC) (Howitt et al. 2007; Hladyz et al. 2011). An excess of DOC can trigger an increase in stream productivity, and the metabolism of the leached carbon by microbes may result in hypoxia if the consumption of dissolved oxygen (DO) from the water occurs at a higher rate than reaeration (Mallin et al. 2006; Howitt et al. 2007; Hladyz et al. 2011; Whitworth et al. 2014). Hypoxic blackwater events can occur naturally, but the severity and frequency of these events can be affected by human influence, such as river regulation and water extraction, which has reduced regular wetting regimes of floodplains (Whitworth et al. 2012; Kerr et al. 2013). Hypoxic blackwater events especially occur during the warmer months when microbial activity is highest. When DO is below 4 $\mathrm{mg\,L^{-1}}$ it

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can have sub-lethal effects on fish and other aquatic organisms, and very low DO below 2 mg L^{-1} can be lethal (Gehrke et al. 1993; La and Cooke 2011; King et al. 2012; Small et al. 2014).

From 1998 to 2010 south-eastern Australia experienced a prolonged drought, often referred to as the Millennium drought, when flows in the Murray–Darling Basin (MDB) were at record low levels (van Dijk et al. 2013; Chiew et al. 2014). After many years without overbank flows, a sequence of floods following the drought triggered a hypoxic blackwater event downstream of large river red gum (*Eucalyptus camaldulensis* Dehnh.) floodplain forests, commencing in September 2010 and persisting until April 2011 (Murray–Darling Basin Authority (MDBA) 2011; Whitworth et al. 2012). At its peak, the blackwater extended for ~1800 river km along the Murray River and in lowland reaches of all major tributaries of the southern MDB. Whitworth et al. (2013) described a range of management strategies used to reduce the severity or impact of hypoxic blackwater events on aquatic biota in the MDB. The interventions include dilution flows, created by releasing water from irrigation canal escapes (regulating structures in canals that enable water to be released into a nearby river channel); physical reaeration of water using paddle wheels, pumps or regulatory structures; and reaeration and dilution by diversion of blackwater into shallow off-channel storages. Whitworth et al. (2013) concluded that while all of these strategies have the potential to promote re-oxygenation of blackwater, in many cases only localised improvements in DO are expected. To date there has been few evaluations of whether these measures can successfully mitigate negative outcomes of hypoxic blackwater events.

Environmental flows (defined in the Brisbane Declaration 2007 as being as the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems) can help restore degraded river ecosystems and mitigate detrimental environmental outcomes of flow alteration (Konrad et al. 2011). The objectives of environmental flow actions are strongly influenced by catchment conditions and availability of water resources. Under medium to high water resource availability, environmental flows have been used to create flood events or pulsed flows to support or promote spawning activity and recruitment of fish (King et al. 2010), breeding of colonial waterbirds (Kingsford and Auld 2005), improve connectivity and primary productivity (Chester and Norris 2006), re-establish more natural erosion and deposition processes (Murle et al. 2003), scour excessive growths of nuisance biofilms (Watts et al. 2010), and flush sediments or algal blooms. Under low water resource availability, small-scale environmental flows have been used to help create refuges and avoid loss of critical taxa during droughts (Rayner et al. 2009). Although the release of environmental flows through irrigation escapes has been suggested as one of the strategies that can promote re-oxygenation of water during hypoxic blackwater events (Whitworth et al. 2013), there are no studies examining whether this type of environmental flow has resulted in good environmental outcomes for aquatic biota.

In this paper, we document ecosystem responses to environmental flows from three irrigation canal escapes in an area of the southern MDB affected by the hypoxic blackwater event in 2010–2011. We hypothesised that reaches receiving an environmental flow would have better water quality and a different fish community to those reaches not receiving an environmental flow. The research draws on data from a number of sources: (1) water chemistry data collected between September 2010 and March 2011 from sites upstream and downstream of three irrigation escapes, (2) fish assemblage surveys in the Edward–Wakool system undertaken before and after the blackwater event, and (3) documents from a government database on fish kills (Fisheries NSW), which records reports of dead fish from fisheries officers, as well as local citizens. We also discuss the use of this information in adaptive management and the implications for future delivery of environmental flows via irrigation escapes.

Methods

Study Area

The Edward–Wakool system is a large anabranch system in the mid-reaches of the Murray River in the southern MDB that has a highly altered flow regime due to river regulation and extraction of water for agriculture (Watts et al. 2015). It was one of the areas in the MDB where hypoxic blackwater was reported in 2010–2011. The Edward River diverges from the Murray River and travels through large river red gum forests and then breaks into a complex network of interconnected streams, ephemeral creeks, and flood-runners before discharging back into the River Murray (Fig. 1). The system is intersected by an extensive irrigation network that is fed by the Mulwala Canal, which diverts water from Lake Mulwala on the Murray River upstream of the red gum forests to create the head required to distribute water via gravity-fed irrigation canals to irrigation areas. There are irrigation canal escapes from the Mulwala Canal to the Edward River, Wakool River, and Yallakool Creek (Fig. 1) that are managed by the irrigator-owned company Murray Irrigation Limited (MIL). The Edward–Wakool system has abundant fish habitat and historically had diverse fish communities which supported both commercial and recreational fisheries (Rowland 2004).

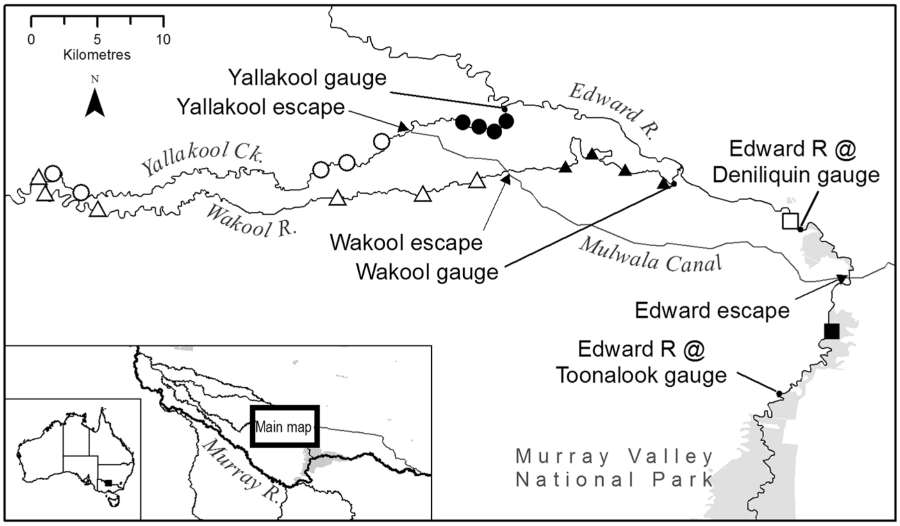


Fig. 1 Map showing location of sites monitored in the Edward River, Wakool River and Yallakool Creek during the blackwater event in 2010–2011. Locations of hydrological gauging sites and the Edward Escape, Wakool Escape, and Yallakool Escape from the Mulwala Canal are shown. Inset maps shows location of study area in the context of the Murray River and south-eastern Australia. Closed square: site upstream of Edward Escape, open square: site in Edward River downstream of Edward Escape. Closed triangles: sites in Wakool River upstream of Wakool Escape, open triangles: sites downstream of Wakool Escape. Closed circles: sites in Yallakool Creek upstream of the Yallakool Escape, open circles: sites downstream of the Yallakool Escape

During the blackwater event in 2010, water was released from three Mulwala Canal escapes to lessen the impact of hypoxia and create localised refugia with higher DO and lower DOC (Whitworth et al. 2013). The Mulwala canal was the only source of water in the affected region that remained well oxygenated and had low DOC that could be utilised for the environmental flow. The canal was not affected by blackwater because the water in the canal is diverted from Lake Mulwala upstream of the red gum forests. Flows through the Wakool irrigation escape commenced in late August 2010 at a time when the flow in the central Murray River was classified as ‘unregulated’, meaning that the flow was higher than required under entitlements and could not be contained by regulating structures, so the flow was not debited to any entitlement account. The flows through the irrigation escapes ceased in early September when the river came under ‘regulated’ conditions. However, after cessation of escape flows, fish kills were observed in the Wakool River. In early October the MDBA, in collaboration with state government agencies, MIL and stakeholders, took the decision to recommence the flows through the irrigation escapes to try to improve water quality where possible. The MDBA (with support from state and federal government agencies) funded the costs of using the MIL-owned escapes to deliver water, and the water used was debited to the annual environmental water entitlements of the MDBA, the (then) NSW State Water Corporation and the Commonwealth Environmental Water Holder. The release of environmental flows through the irrigation canal escapes continued until May 2011.

Data Sources

Daily stream discharge data were obtained from the NSW Government Waterinfo website for the following automated gauges: Yallakool Creek at the offtake from the Edward River (gauge 409020), Wakool River offtake regulator (gauge 409019), Edward River at Toonalook (gauge 409047), and Edward Escape from Mulwala canal (gauge 409029) (Fig. 1). Daily discharge data from the Wakool Escape and Yallakool Escape are not reported on the Waterinfo website and were obtained from the New South Wales State Water Corporation (now WaterNSW).

Water samples were collected from 22 sites in the Edward–Wakool system (Fig. 1) on ten occasions between September 2010 and March 2011, incorporating dates before, during, and after flow peaks. In the Edward River, samples were collected from one site upstream and one site downstream of the Edward Escape, in Yallakool Creek there were four sites upstream and five sites downstream of the Yallakool Escape, and in the Wakool River there were four sites upstream and five sites downstream of the Wakool Escape (Fig. 1). One additional site downstream of the junction of Yallakool Creek and the Wakool River and one site in the Mulwala Canal near the Wakool Escape were also sampled.

Water temperature (°C) and DO (reported as mg O_2 L^{-1}) were measured at each site on each sample date along with other water quality parameters (Howitt et al. unpublished data) that are not reported here because a full analysis of water chemistry during the blackwater event is beyond the scope of this paper. DO concentrations were assessed against two thresholds; (i) a sub-lethal threshold of 4 mg L^{-1} below which fish are known to be stressed (King et al. 2012; Small et al. 2014), and (ii) a lethal threshold below which fish have been reported to die (Gehrke et al. 1993; La and Cooke 2011; King et al. 2012; Small et al. 2014).

Fish assemblage data were obtained from a system-wide monitoring programme that was established in 2010 by the (then) Murray Catchment Management Authority in collaboration with the New South Wales Department of Primary Industries (Fisheries) to provide baseline information on native fish population status in the Edward–Wakool system, facilitated through a Strategic Adaptive Management Programme being implemented by the Murray Catchment Management Authority (Baumgartner et al. 2014). Fish were surveyed at 19 river sites within the Edward–Wakool system in 2010 prior to the blackwater event, and again in 2011 and 2012 after the blackwater event. Fish were collected using a standardised electrofishing protocol including 10 bait traps established by the Sustainable Rivers Audit for the MDB (Davies et al. 2010). This was augmented by a netting strategy to capture any cryptic species that may have been present. This involved setting two 15 m long (2 m drop) monofilament multi-panel gill nets with single 35, 75, 100 mm mesh panels for two hours. Additionally, two 3 mm dual wing fyke nets and two 25 mm single wing fyke nets were set and retrieved the following day to encompass diurnal periods. At the completion of each electrofishing and netting operation, all fish were identified, counted and measured (maximum of 50 individuals per species per survey).

Information on dead fish within the Edward–Wakool system during the 2010–2011 blackwater event was obtained from the New South Wales Department of Primary Industries Fish Kill database. This database includes internal Fish Kill Notification and Investigation Reports, photos, reports, and email notifications from community members.

Results

Environmental Flows from the Irrigation Escapes

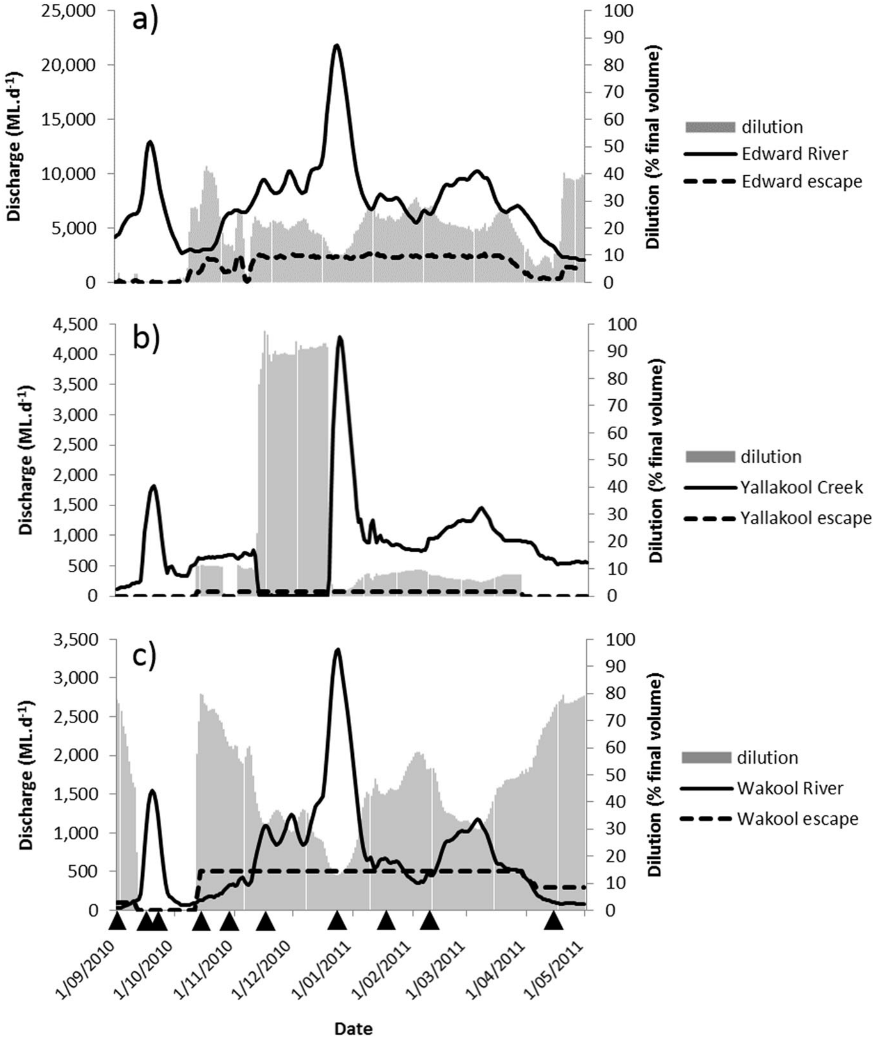
Unregulated water was initially released from the Wakool Escape from late August 2010 until early September (Fig. 2). Between early September and early October no water was released from the canal escapes, but in early October environmental flows re-commenced through the Edward, Yallakool, and Wakool escapes (Fig. 2). An average of 2500 ML d^{-1} (28.93 $m^3 s^{-1}$) of environmental water was released from the Edward Escape to the Edward River between October 2010 and early March 2011 (Fig. 2a), and the dilution effect (the percent that the water from the escape contributed to the total flow in each system on a daily basis) of this water was ~20–25%, except during a large flow pulse in December 2010, when the escape water contributed ~10% of the total flow. In contrast, only a very small volume of water was released from the Yallakool Escape to Yallakool Creek. Despite the small volume, this environmental flow contributed almost 90% of the total flow in Yallakool Creek in November and December 2010, because the Yallakool Creek regulator was being repaired and the discharge through the regulator was extremely low at that time. However, from January through to May 2011 the contribution of the water from the Yallakool Escape to Yallakool Creek was less than 10% of total flow (Fig. 2b). Approximately 500 ML d^{-1} (5.78 $m^3 s^{-1}$) was delivered from the Wakool Escape to the Wakool River from early October 2010 to March 2011, tapering down to 300 ML d^{-1} (3.47 $m^3 s^{-1}$) during April 2011 (Fig. 2c). This contributed between 15 and 80% of the total flow in this system, with the lowest contribution being during the large flow pulse in December 2010 (Fig. 2c).

Water Quality

Mean water temperatures across all sites was less than 15 °C during September 2010 whereas in late November and in December the mean water temperature was greater than 20 °C (Fig. 3a). This corresponded with two peaks in DOC of 14 mg L^{-1} in September and 15 mg L^{-1} in December, but with two sites recording DOC above 17 mg L^{-1} during the second peak (Howitt et al. unpublished data). The mean concentration of DO across all sites was above 6 mg L^{-1} during September and October 2010 but reduced rapidly in November 2011 and was below the sub-lethal threshold of 4 mg L^{-1} in December 2010 during the large flow pulse, increasing to above 4 mg L^{-1} in January 2011 (Fig. 3b). Mean DO across all sites did not fall below the lethal threshold of 2 mg L^{-1}.

There was a positive influence of the environmental flows from the Edward Escape on the concentration of DO in the Edward River downstream of the escape. The DO in the Edward River upstream of the Edward Escape was below the 4 mg L^{-1} sub-lethal threshold from late October 2010 until early February 2011 and was below the 2 mg L^{-1} lethal threshold from mid-November 2010 until early January 2011 (Fig. 4a). In contrast, the DO in the Edward River downstream of the escape was below the sub-lethal threshold between mid-November and mid-January (approximately a month less than upstream of the escape), and the DO was never below the lethal threshold (Fig. 4a).

Fig. 2 Hydrographs of the daily discharge (ML d^{-1}) at **a** the Edward River at Toonalook (gauge 409047) and Edward Escape from Mulwala Canal (gauge 409029), **b** Yallakool Creek offtake (gauge 409020) and Yallakool Escape, and **c** Wakool River at offtake regulator (gauge 409019) and Wakool Escape. Shaded area shows the percent that the water from the escape contributed to the total flow in each system on a daily basis. Triangles indicate the timing of the ten dates when water quality was monitored. Note that the *y* axes for discharge have different values



There was also a positive influence of the environmental flows from the Wakool Escape on the concentration of DO in the Wakool River. The concentration of DO in the Wakool River upstream of the escape was below the sub-lethal threshold from early November 2010 until mid-January 2011, and in late December was briefly below the lethal threshold (Fig. 4c). In contrast, in reaches of the Wakool River downstream of the Wakool Escape the DO was below the sub-lethal threshold between mid-November and early January (approximately a month less than upstream of the escape), and was never recorded below the lethal threshold during this blackwater event (Fig. 4c).

In contrast to the Edward River and Wakool River responses, there was limited influence of the flows from the Yallakool Escape on the concentration of DO in Yallakool Creek. Measurements of DO were similar between the upstream and downstream sites (Fig. 4b), which reflects the smaller contribution of the water from the Yallakool Escape to the total flow in this creek (Fig3b) The concentration of DO was briefly lower in the reach downstream of the escape than in the reach upstream of the escape on two occasions, in October 2010 and January 2011 (Fig. 4b).

The delivery of the water from the escapes created improved DO conditions for at least 40 km downstream of the Wakool Escape. On 21st December at all four sites upstream of the Wakool Escape, DO was below the 2 mg L^{-1} lethal threshold, whereas at all six sites downstream of the escape DO was above 2.5 mg L^{-1}. On the 18th January at all sites upstream of the Wakool Escape, DO was below the 4 mg L^{-1} sub-lethal threshold, whereas at all sites downstream of the escape DO was well above this critical threshold (Fig. 5). The similarity in DO at sites 2 km and 40 km downstream of the Wakool Escape suggests that the canal water is well mixed with the river water a short distance downstream of the irrigation canal escape.

Fish Surveys and Reports of Dead Fish

Ten native species and five invasive species were collected across 19 survey sites in the Edward–Wakool system. Prior

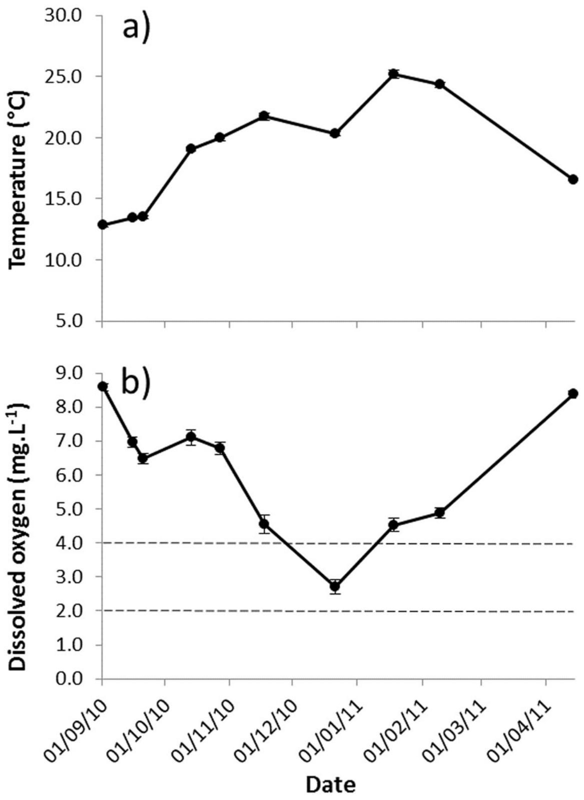


Fig. 3 **a** Mean dissolved oxygen (DO) concentrations (mg L^{-1})(±SE) across all sites and **b** mean temperature (°C) (±SE) across all sites. Horizontal lines on the DO graph indicate critical thresholds at which fish are known to be stressed (4 mg L^{-1}) or die (2 mg L^{-1})

to the blackwater event, small-bodied native fish (carp gudgeon *Hypseleotris* spp., Murray River rainbowfish *Melanotaenia fluviatilis*, Australian smelt *Retropinna semoni*, and unspecked hardyhead *Craterocephalus stercusmuscarum fulvus*) dominated the catches (Fig. 6), but the biomass was dominated by common carp *Cyrpinus carpio* and goldfish *Carrassius auratus*. Native fish kills occurred extensively during the hypoxic blackwater event, and after the blackwater event common carp and goldfish became the dominant species in terms of both biomass and number of individuals (Fig. 6).

In May 2010, prior to the blackwater event, Murray cod (*Maccullochella peelii*) were present at all of the fish survey sites in the Edward–Wakool system (Fig. 7), but after the event they were captured from only the four sites located in river reaches immediately downstream of the Edward Escape and Wakool Escape (Fig. 7). Records of dead fish in the Edward–Wakool system during the 2010–2011 blackwater event from the NSW Department of Primary Industries Fish Kill database concur with the fish survey results. During the blackwater event dead fish were reported throughout the middle and lower reaches of the system, but not in the section of river immediately downstream of the irrigation escapes (Fig. 7).

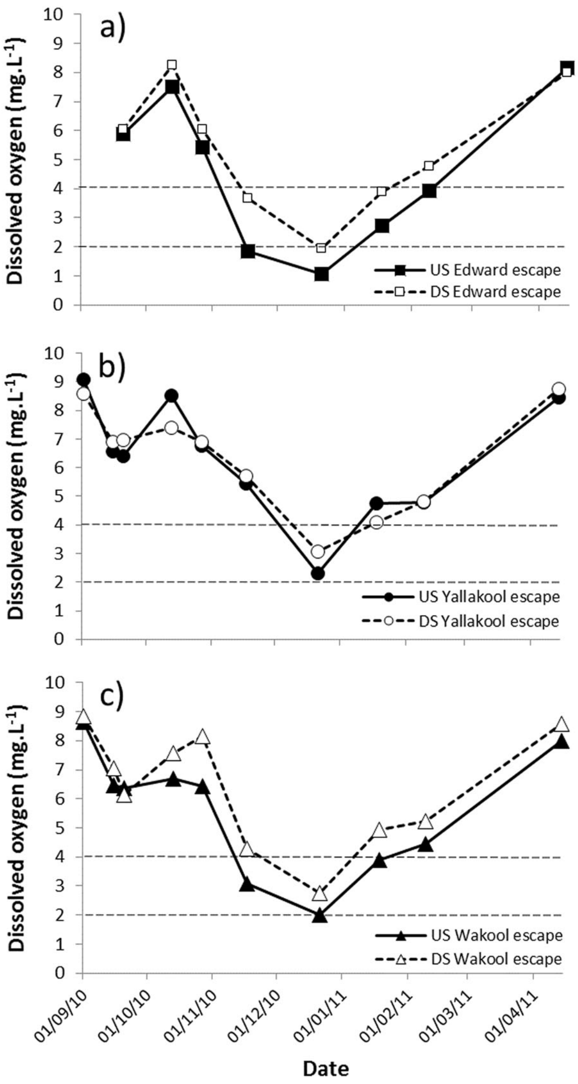


Fig. 4 Dissolved oxygen (DO) concentrations (mg L^{-1}) from sites upstream and downstream of the **a** Edward Escape, **b** Yallakool Escape, and **c** Wakool Escape from Mulwala canal. Closed squares: site upstream of Edward Escape, open squares: site in Edward River downstream of Edward Escape. Closed circles: sites in Yallakool Creek upstream of the Yallakool Escape, open circles: sites downstream of the Yallakool Escape. Closed triangles: sites in Wakool River upstream of Wakool Escape, open triangles: sites downstream of Wakool Escape. Horizontal lines indicate critical levels at which fish are known to be stressed (4 mg L^{-1}) or die (2 mg L^{-1})

Discussion

Outcomes of the Delivery of Environmental Flows from Irrigation Escapes

While there is considerable literature describing the circumstances that can lead to the development of hypoxic blackwater (e.g. Howitt et al. 2007, Hladyz et al. 2011), this event in the Edward–Wakool system in 2010–2011 is the first documented case where environmental flows delivered

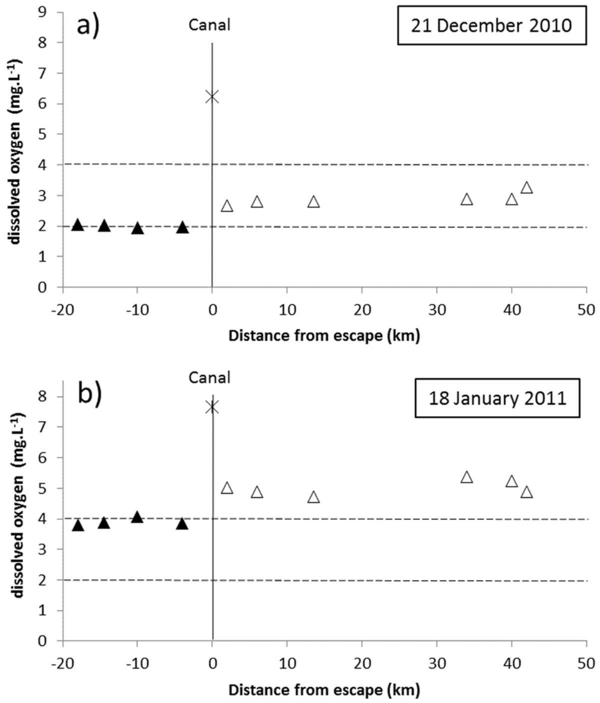


Fig. 5 Dissolved oxygen (DO) concentrations (mg L^{-1}) in the Mulwala Canal, at four sites in the Wakool River upstream of the Wakool Escape and six sites in the Wakool River downstream of the Wakool Escape on 21st December 2010 and 18th January 2011. Open triangles: sites in Wakool River upstream of Wakool Escape, open triangles: sites in the Wakool River downstream of Wakool Escape. Asterisk indicates the sample collected from the Mulwala canal. Horizontal lines indicate critical thresholds at which fish are known to be stressed (4 mg L^{-1}) or die (2 mg L^{-1}). The increase in DO concentration above critical thresholds persisted for more than 40 river km downstream of the Wakool Escape

from irrigation canal escapes have been shown to mitigate hypoxic blackwater and result in the creation of local refuges for aquatic biota. The flows from the irrigation escapes increased the concentration of DO by between 1 and 2 mg L^{-1}. While this increase in DO was relatively modest, it reduced the number of days that the DO was below the sub-lethal threshold by approximately one month, and prevented the DO from dropping below the lethal threshold. Most importantly, the improvement in DO was observed at least 40 km downstream of the Wakool Escape, encompassing a deep water hole at the confluence of the Wakool River and Yallakool Creek that is a critical habitat for fish in the this part of the Edward–Wakool river system (Watts et al. 2014). Thus the release of water through the irrigation canal escapes was an effective management option for mitigating the negative effects of hypoxic blackwater by creating critical refuge in this system.

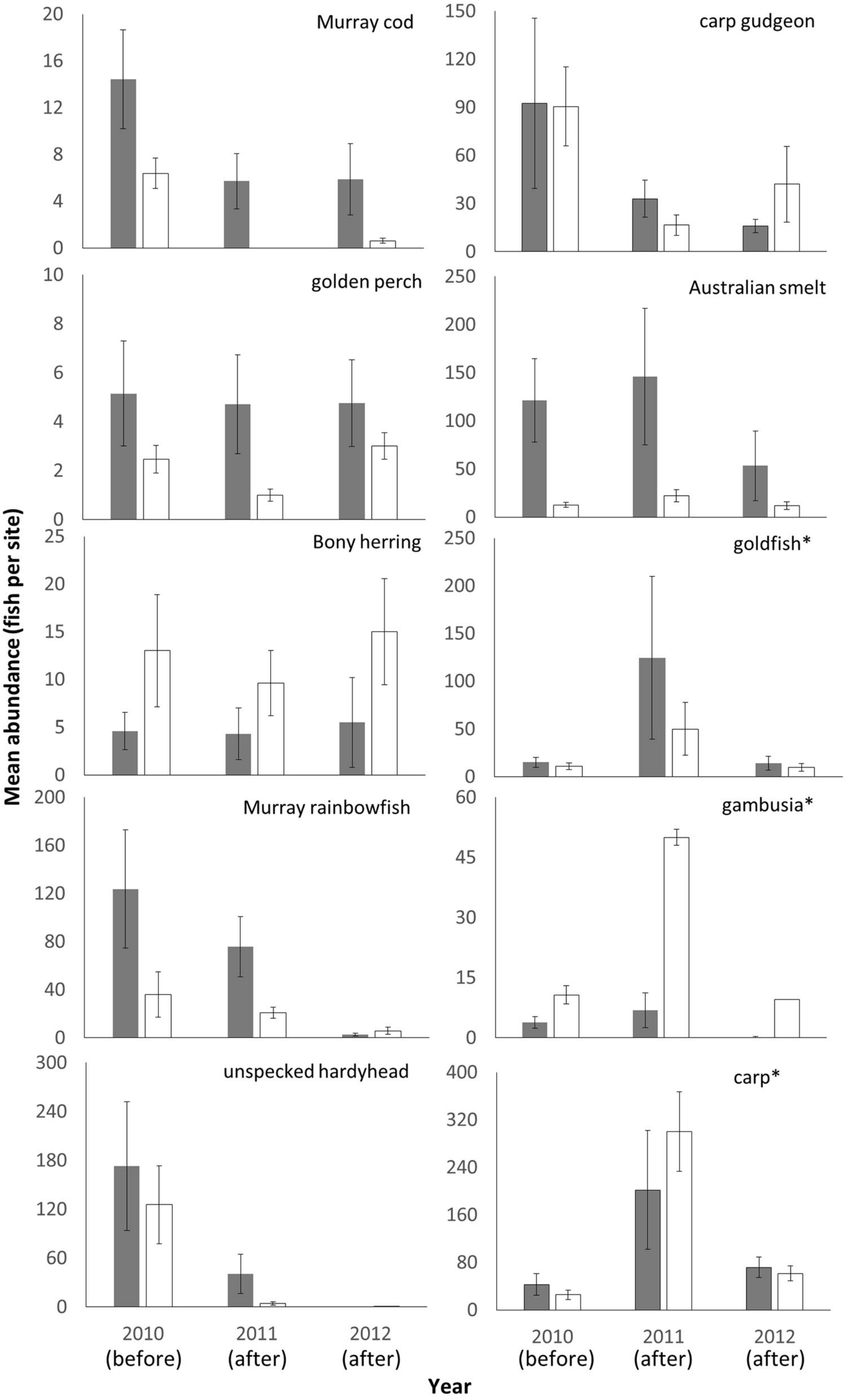
The outcome of creating refuges from hypoxic blackwater was evident in the results of the fish assemblage surveys and fish kill reports. In the two years after the blackwater event the iconic large-bodied native fish Murray cod continued to occupy the reaches that received environmental flows, whereas in areas outside the refuge zone there were widespread reports of dead Murray cod during the hypoxic blackwater event and they were absent from all reaches outside the refuge zone in the year immediately after the blackwater event. Although there were no reports of dead larvae or very small fish during the hypoxic event, this is not surprising, because in the summer months small fish would rapidly decompose and would not be easy to detect. However, it is highly likely that the hypoxic blackwater had detrimental effects on larval and juvenile fish, because a laboratory-based study has shown that juvenile stages of large-bodied fish are vulnerable to mortality induced by low oxygen concentration and water chemistry changes associated with the decomposition of organic material (Small et al. 2014).

The refuges created by the environmental flows were critical for the recovery of fish populations in this river system. Adult fish that survived the hypoxic blackwater event recolonised the effected reaches within 5 years, whereas the release of stocked fish to help fish populations recover was less effective than natural recruitment (Thiem et al. 2016). Effects of hypoxia at a population level are often difficult to demonstrate, in part because exposure to low oxygen is often ephemeral due to avoidance behaviour, resulting in temporary shifts in spatial distribution (e.g. Brady and Targett 2013). However, as the hypoxic blackwater event in the Murray River system extended over 1800 km, it would not have been possible for fish to migrate out of the affected area to avoid the event. Therefore, the provision of refuge areas within the affected zone was critical for the recovery of fish in this system.

The magnitude of the DO response to this management strategy was highly dependent on the extent to which the water from the escape contributed to the total flow in the receiving river system. The flows from the escapes contributed between 20 and 80% of the flow in the Edward and Wakool Rivers and had notable outcomes on DO in these systems, whereas the flow from Yallakool Escape contributed less than 10% of the total flow in that system and had limited influence on the concentration of DO. The Yallakool Escape had a lower release capacity than the other two escapes, demonstrating that the capacity of infrastructure can influence outcomes. As the majority of the water regulatory structures in the MDB were originally constructed to deliver water for irrigation, this example raises the possibility that existing irrigation infrastructure could be modified to better serve multiple functions. If the costs of maintenance and upgrade of infrastructure were shared by different users, there could be benefits for both environmental and economic outcomes.

The magnitude of the ecosystem response to this type of management action was also strongly influenced by

Fig. 6 An interaction plot comparing mean fish abundance among sites where environmental flows successfully increased dissolved oxygen (grey) and those sites where the environmental flows had no impact (white). The results from 2010 were from before the blackwater event and the results from 2011 and 2012 were from after the blackwater event



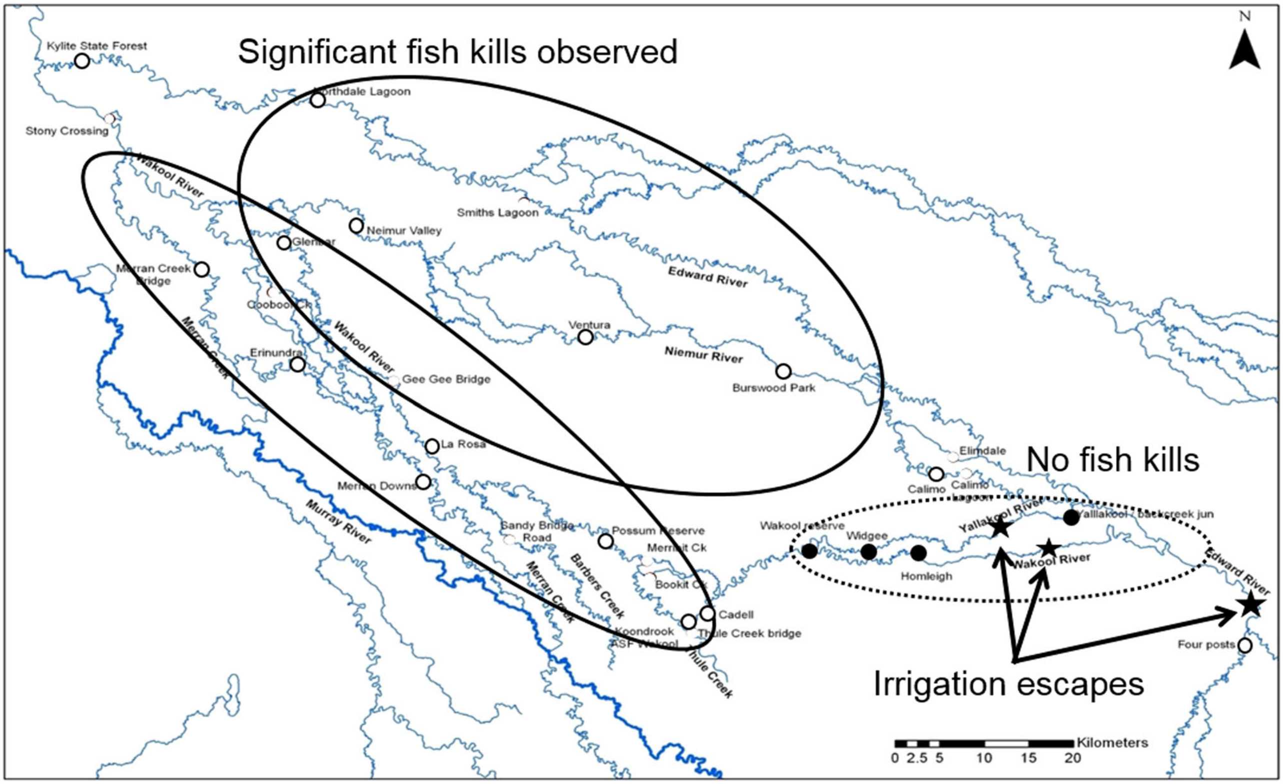


Fig. 7 Map showing location of irrigation escapes and area where dead fish were recorded by agency staff and community members during the 2010–2011 hypoxic blackwater event in the Edward–Wakool system, southern Murray–Darling Basin. Open circles are based on the results of fish surveys, showing locations where Murray cod were present in 2010 but absent in 2011. Closed circles show locations where Murray cod was present in both 2010 and 2011. Stars show the location of the three irrigation canal escapes through which environmental flows were delivered to river reaches

seasonal conditions. The lower water temperature during the flow pulse in September 2010 resulted in minimal effects on DO, despite a slight increase in river metabolism associated with export of DOC from the Barmah-Millewa forests (Cook et al. 2015). However, during the peak in river discharge in late December 2010 the water temperatures were considerably higher and this contributed to the rapid reduction in DO. Thus the management action to release water through the escapes was critical during the warmer summer months but was less urgent during the cooler spring months.

The use of irrigation infrastructure to deliver environmental outcomes is not new in Australia. Irrigation pumps, channels, and regulators have been widely used to deliver water to floodplain wetlands (e.g. Meredith and Beesley 2009). However, to our knowledge, there are no previous reports of irrigation canals being used to create refuges in rivers during a hypoxic blackwater event. Implementation of environmental flows through irrigation canal infrastructure would be an effective management option in other countries that have established irrigation networks and infrastructure. Whitworth et al. (2013) described a range of management strategies that were used to reduce the severity or impact of hypoxic blackwater events on aquatic biota in the MDB, and concluded that while all of the strategies have the potential to promote re-oxygenation of blackwater, in many cases only localised improvements in DO are expected. This current study has demonstrated that, when conditions are appropriate, release of water from irrigation canal escapes has the potential to improve oxygenation of water over a considerable length of river, thus resulting in better outcomes than some of the physical reaeration methods, such as paddle wheels or pumps, that are more likely to have only localised benefits (Whitworth et al. 2013).

This study has demonstrated that under certain environmental conditions the use of irrigation escapes to deliver environmental flows can produce excellent environmental outcomes and is an appropriate strategy to mitigate detrimental outcomes and prevent critical loss. The Australian government has developed a framework for determining the use of environmental water (CEWO 2013) that informs decision making under different levels of water resource availability (Table 1). This recognises that the scope of watering actions and the environmental outcomes that can be achieved will be limited by availability of water (referred

Table 1 Framework developed by the Australian commonwealth environmental water office for determining the range of environmental outcomes and portfolio management actions in scope for Commonwealth environmental water under different levels of water resource availability. (Source: CEWO 2013)

	Water resource availability				
	Very Low	Low	Moderate	High	Very High
Purpose	Avoid damage to key environmental assets	Ensure ecological capacity for recovery	Maintain ecological health and resilience	Improve the health and resilience of aquatic ecosystems	Build future capacity to support ecological health and resilience
Environmental outcomes in scope	•Avoid critical loss of species, communities and ecosystems •Maintain key refuges •Avoid irretrievable damage or catastrophic events	•Support the survival and viability of threatened species and communities •Maintain refuges •Maintain environmental assets and ecosystem functions	•Enable growth, reproduction and small-scale recruitment for a diverse range of flora and fauna •Promote low-lying floodplain-river connectivity •Support medium flow river and floodplain functional processes	•Enable growth, reproduction and large-scale recruitment for a diverse range of flora and fauna •Promote higher floodplain-river connectivity •Support high flow river and floodplain functional processes	•Enable growth, reproduction and large-scale recruitment for a diverse range of flora and fauna •Sustain higher floodplain-river connectivity •Support high flow river and floodplain functional processes
Portfolio management options in scope	•Allow drying to occur, where appropriate •Water refuges and sites supporting threatened species and communities •Undertake emergency watering at specific sites of priority assets •Use carryover volumes to maintain critical needs	•Allow drying to occur consistent with natural wetting-drying cycles •Water refuges and sites supporting threatened species and communities •Provide low flow and freshes in sites and reaches of priority assets •Use carryover volumes to maintain follow-up watering	•Prolong flood/high-flow duration at key sites and reaches of priority assets •Contribute to the full-range of in-channel flows •Use carryover to provide optimal seasonal flow patterns in subsequent years	•Increase flood/high-flow duration and extent across priority assets, where feasible •Contribute to the full range of flows incl. over-bank, where feasible •Use carryover to provide optimal seasonal flow patterns in subsequent years	•Maintain flood/high-flow duration and extent across priority assets, where feasible •Contribute to the full range of flows incl. over-bank, where feasible •Use carryover to provide reserves for future years

to as ‘supply’) to achieve these outcomes (CEWO 2013). Under this framework, the objective to ‘avoid damage’ to key environmental assets is included only under the ‘very low’ water resource availability scenario. However, the current study demonstrates that this objective can also be achieved under low, moderate, high and very high water resource scenarios if there are opportunities to create refugia and support threatened species and communities during hypoxic blackwater events.

Adaptive management

Governments and water management agencies around the world have made progress in developing policies or laws to protect or deliver environmental flows (Le Quesne et al. 2010) through the protection of natural flows, restricting water abstraction or by modifying dam operations (e.g. Richter and Thomas 2007; Watts et al. 2011). However, implementation of these policies has been limited by a range of factors including availability of water, limitation of infrastructure to deliver environmental flows, and governance issues. It has been acknowledged that engagement with a broader community of stakeholders is essential for effective and timely implementation of environmental flows (Matthews et al. 2014).

Effective stakeholder engagement and established networks contributed to the success of the management of the hypoxic blackwater event in the Edward–Wakool system in 2010–2011. Prior to the blackwater event, a strong network among agencies and researchers working in the Edward–Wakool system had been established and decisions about flow delivery was a multi-stakeholder driven process, involving weekly to fortnightly teleconferences where water delivery and operations were discussed. When the blackwater event occurred these existing networks facilitated timely interactions and communication across organisations during the event so that researchers, agency staff, and community members were able to provide real time information to water managers to help inform their water management decisions.

An established monitoring regime to provide data to underpin management decisions was another of the key elements of the adaptive management of environmental flows during this hypoxic blackwater event. Over the course of the blackwater event, members of this network (including community members) regularly monitored DO throughout the river system, particularly in reaches where there were no automated hydrographic stations. Similarly, agency staff, landholders and other community members contributed information on the location of dead fish, adding critical information to the Department of Primary Industries Fish Kill database. All of this information contributed to real time decision making and enabled managers to make decisions about the delivery of environmental flows. For example, when the September flow pulse had subsided and the river became ‘regulated’, the MDBA, along with other state and federal government agencies, were required to make a decision whether or not to continue the delivery of environmental water through the escapes. This decision had cost implications, as the use of the MIL-owned irrigation escapes incurred delivery costs, and any water used would have to be debited against held licences. So for a period of time in September through to early October there were no environmental flows released through the irrigation escapes. However, the hypoxic conditions continued and more dead fish were reported, resulting in active lobbying by stakeholders for action to be taken. This, along with monitoring data contributed by scientists, agencies, and the community, underpinned the critical water management decision to recommence the environmental flows through the irrigation escapes to try to improve water quality where possible.

This study demonstrates how adaptive management occurs through collaboration among organisations and stakeholders, and through the timely provision of local knowledge and expertise. Difficult management decisions are more likely to be taken when there is necessary data available and when there is participatory decision making. Public acceptance and participation is pivotal to achieving effective and enduring natural resource outcomes (Carpenter and Biggs 2009).

The knowledge generated by this project has assisted water managers to improve the delivery of environmental flows in the Edward–Wakool system, and it has the potential to assist other environmental flows programmes elsewhere. For example, the results of this study were used to predict expected outcomes of the delivery of environmental water from irrigation infrastructure during a subsequent blackwater event in the Edward–Wakool system in late 2016. The project provides an example of the important contribution of environmental flows toward preventing damage and loss of critical taxa in the MDB. It is essential to share this message with the broader Australian and international community so there is a better understanding of the types of outcomes that can be achieved for the environment and society through the use of environmental flows. Future delivery of environmental water from irrigation infrastructure could be improved and optimised by undertaking modelling to predict the outcomes of proposed management actions. Furthermore, a cost–benefit analysis of these management actions could be undertaken to assess the value of releasing environmental water during hypoxic blackwater events.

Acknowledgements The authors thank Edward–Wakool landholders, the Wakool River Association and the Edward–Wakool Anglers Association for their interest in the project and providing access to monitoring sites on their properties. Thank you to James Dyer and Elena Griffiths for field assistance. Figure one was prepared by Deanna Duffy (Charles Sturt University Spatial Analysis Unit). Fish collections were carried out under New South Wales Animal Care and Ethics Authority 10/01 and Scientific Collection Permit P01/0059 (A). Funding for the water quality monitoring was provided by Charles Sturt University and also funding to the (then) Murray Catchment Management Authority (MCMA) by the Australian Government under the Caring for our Country Programme. Funding for the fish surveys was provided by the MCMA, New South Wales Department of Primary Industries (Fisheries) and the (then) Department of the Environment, Heritage, Water and the Arts. Thanks to the editor and several reviewers for their constructive comments on drafts of this manuscript.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no competing interests.

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